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Emulsifying and Foaming Properties of Commercial Yellow Pea (*Pisum sativum* L.) Seed Flours

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Commercial yellow pea seed flours prepared by a patented wet-milling process and pea protein isolate (PPI) were analyzed for emulsifying and foaming properties at pH 3.0, 5.0, and 7.0 and compared to soybean protein isolate (SPI). PPI and SPI formed emulsions with significantly smaller ($p < 0.05$) oil droplet sizes, 16−30 and 23−54 μm, respectively, than flours that primarily contained fiber such as Centara III and IV, or those that consisted mainly of starch: Centu-tex, Uptake 80 and Accu-gel. PPI was a better emulsifier than SPI at pH 7.0, and a better foaming agent at pH 3.0 and pH 7.0, although foaming capacity varied with sample concentration. Centu-tex and Uptake 80 have exactly the same chemical composition, but the latter has a much smaller flour particle size range, and had significantly smaller ($p < 0.05$) emulsion oil droplets. Incorporation of pea starch into SPI emulsions produced a synergistic effect that led to significant increases ($p < 0.05$) in emulsification capacity (reduced emulsion oil droplet size) when compared to SPI or starch alone. These results showed that PPI had generally significantly higher ($p < 0.05$) emulsion and foam forming properties than SPI, and that pea starch could be used to improve the quality of SPI-stabilized food emulsions.

KEYWORDS: Pea; seed flour; soybean; protein isolate; starch; emulsion; foaming

INTRODUCTION

Yellow field pea seeds (*Pisum sativum* L.) are the main raw materials in the commercial production of various food-grade flour fractions that are predominantly protein, starch, fiber or starch and fiber combinations. There has been increased interest in plant-derived food ingredients such as those from pea seeds because of consumers' demand for cholesterol-free and low-fat food products. Soybean seeds remain the primary source of plant-based food ingredients, but yellow field pea products can be used to give similar nutritive and functional properties to food and beverage formulations. For example, under appropriate conditions, commercial or laboratory-prepared pea protein isolates were able to form good protein gels though they had less gel strength when compared to similar soybean protein products (*1*−*3*). However, additional functional properties of pea seed flours need to be properly elucidated to facilitate their application in the formulation of either new or traditional foods.

Typically, yellow field peas have up to 25% protein content, 55−68% starch and 6.5% fiber (*4*, *5*). The pea seed proteins consist of mostly the 11S (legumin), 7S (vicillin) and 2S (albumins); however, the protein isolates are composed mainly of the 11S and 7S storage proteins as evident from gel electrophoresis (*1*). Pea seeds can be separated into the hulls, which are used to produce high fiber flours, and the dehulled seeds, which can be processed by pin milling and air classification to give protein-enriched and starch-enriched flour fractions (*4*). The dehulled seeds can also be processed by wet milling to obtain purified fractions of fiber, starch, and protein. These purified flours have better functionality for some types of food applications than the enriched air classified flours (*4*).

Emulsification and foaming are two of the most important functionalities that proteins and other amphoteric molecules contribute to in the development of traditional or novel foods (*6*). During emulsification these ingredients facilitate stable oil droplet formation through development of interfacial membranes. The membranes prevent coalescence of droplets, and so enhance droplet dispersion in the immiscible phase of the emulsion (*7*−*9*). Carbohydrates such as starch and fiber may also enhance emulsion stability by acting as bulky barriers between the oil droplets, preventing or slowing down the rate of oil droplet coalescence. Foam formation and stability are also dependent on interfacial membrane formation or barrier establishment to prevent coalescence of air bubbles (*8*, *9*). Therefore, apart from the use of products that consist mostly of proteins or starch, it may be possible to form and stabilize emulsions and foams with suitable combinations of both products.

Though various pea flour products are currently produced in commercial quantities, utilization in food formulation is limited due to a lack of information on their functional properties. In order to enhance acceptability of pea seed flours and increase usage for the formulation of foods, there is the need to provide some basic information on their ability to act as emulsifiers and foaming agents. The objectives of this work were to determine the emulsifying and foaming properties of yellow pea protein isolate, and of high starch and fiber flours, and to

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Table 1. Percent Proximate Composition (Dry Weight Basis) of Commercial Flours from Yellow Field Pea Seed and Soybean Seeds

name	protein ($N \times 6.25$)	lipids	fiber	starch	sugars	ash
Accu-Gel	1.0	0.1	0.0	98.7	0.0	0.2
Centara III	6.0	0.5	90.0	0.1	0.5	2.0
Centara IV	3.0	0.5	93.0	0.0	1.5	2.0
Centu-Tex (425 μm)	10.0	0.5	35.0	50.0	2.5	2.0
Uptake 80 (175 μm)	10.0	0.5	35.0	50.0	2.5	2.0
Propulse (pea protein isolate)	82.0	0.3	0.0	0.7	11.7	4.0
soy protein isolate	90.0	4.0	0.0	0.0	<1.0	5.0

determine the influence of pea starch on the performance of the protein isolates.

MATERIALS AND METHODS

Materials. Pea flour products (from nongenetically modified seeds) were obtained as gifts from the Nutri-Pea Ltd. company (Portage la Prairie, Manitoba, Canada). Details of production of the yellow field pea seed ingredients are proprietary (*10*). In general the process involves a similar procedure to the one described by Sosulski and McCurdy (*4*). Briefly, the peas are dehulled and ground into flour, which is passed through a screen to separate the coarse fiber particles. The flow-through flour is then extracted with an acidic solution and centrifuged, and the supernatant is used for isoelectric protein precipitation. This gives a protein concentrate (about 85% protein) while the residue is used as a source of starch, and a starch-fiber composite flour. The hulls are ground separately to produce very high fiber flours. In this work we used two high fiber (>90%) products, Centara III and Centara IV, and two starch-fiber products, Centu-Tex and Uptake 80, as well as one pea protein isolate (Propulse) and one high starch (>98%) product, Accu-Gel, as shown in **Table 1**. Soybean protein isolate (SPI, PRO-FAM 974) that was used for comparison purpose was a gift from Archer Daniels Midland Company (ADM, Decatur, IL). Data on the proximate composition of all the flours were provided by Nutri-Pea Ltd. (pea flours) or ADM (soy protein isolate) and are shown in **Table 1**.

Emulsion Formation and Measurement. Oil-in-water emulsions were prepared as previously described by Aluko and McIntosh (*11*) with the following modifications. Using the different ingredients or mixtures of protein and starch, slurries were prepared in 5 mL of 0.1 M phosphate buffer pH 3.0, 5.0, or 7.0 followed by addition of 0.5 mL of pure canola oil (10%, v/v). The oil/water mixture was homogenized at 20,000 rpm for 1 min, stopped for 5 s and then homogenized again for another 1 min using the 20 mm nonfoaming shaft on a Polytron PT 3100 homogenizer (Kinematica AG, Lucerne, Switzerland). The oil droplet size ($d_{3,2}$) of the emulsions was determined in a Mastersizer 2000 (Malvern Instruments Ltd., Malvern, U.K.) with distilled water as dispersant. Emulsion sample was added (under constant shearing) to about 100 mL of water contained in the small volume wet sample dispersion unit (Hydro 2000S) attached to the instrument until the required level of obscuration was attained. The instrument was set to measure each emulsion in triplicate and to calculate the mean value; each emulsion was prepared twice. Emulsions were left at room temperature for 30 min, after which the oil droplet size measurement was repeated. Emulsion stability was determined as the percentage ratio of initial to the 30 min $d_{3,2}$ values.

Foam Formation and Measurement. Foams were formed as previously described (*11*) with the following modifications. Slurries were prepared in 10 mL of 0.1 M phosphate buffer pH 3.0, 5.0, or 7.0 followed by homogenization at 20,000 rpm for 1 min using a 20 mm foaming shaft on the Polytron PT 3100 homogenizer. The foam was formed in a 50 mL graduated centrifuge tube, which enabled determination of foam volume (mL). Each sample was analyzed in triplicate, and the mean value is reported. The volume of foam remaining after 30 min at room temperature was expressed as a percent value of original foam volume to obtain foam stability.

Statistical Analysis. Analysis of variance and Duncan's multiple range tests were performed to determine significant differences between mean values within each group using the Statistical Analysis Systems (SAS) desktop software, version 9.1.

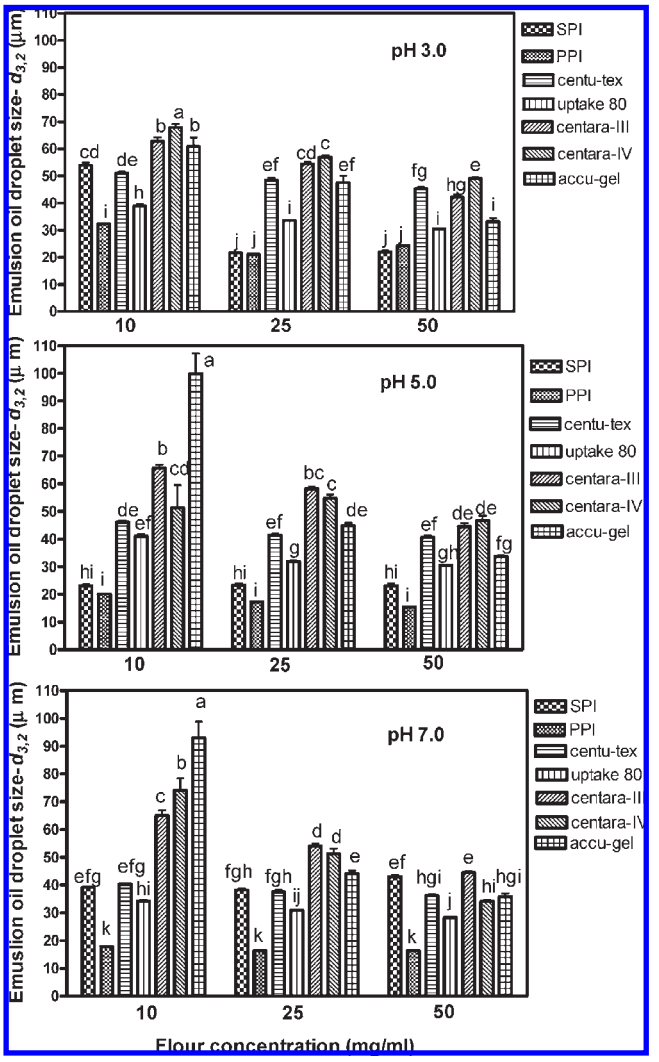

Figure 1. Effect of pH on the emulsifying capacity (oil droplet size) of soybean protein isolate (SPI, 90% protein) and pea seed flours: Centara III and Centara IV (high fiber, >90%); Centu-Tex and Uptake 80 (starch, 35%-fiber, 50%), Accu-Gel, high starch (>98%), pea protein isolate (PPI, 82% protein). For each box plot, bars with different letters are significantly different ($p < 0.05$).

RESULTS AND DISCUSSION

Effect of Sample Concentration and pH on Emulsion Formation and Stability. The effects of sample concentration and pH on the oil droplet size of emulsions stabilized by pea seed flours are shown in **Figure 1**. Increased sample concentration, from 10 to 50 mg/mL, produced beneficial effects on emulsification (reduced droplet size) at all pH values for Centu-tex, Uptake 80, Centara III and IV and Accu-gel. These flours all have low protein content (≤10%). There were no significant concentration effects ($p < 0.05$) on emulsification ability of the soy protein isolate (SPI) and the pea protein isolate (PPI) at pH 5.0 and pH 7.0, but droplet size was reduced with the higher concentrations at pH 3.0. At pH 3.0, 5.0, and 7.0, the two isolates produced emulsions with smaller droplets (16−54 μm) than did the flours that contained lower amounts of protein (≤10%), which had droplet sizes of 30−100 μm. Within this group of higher starch flours, Centu-tex and Uptake 80 (10% protein) produced emulsions that had smaller droplets (34−50 μm), and therefore better quality, than Centara III and IV and Accu-gel (1−6% protein) that had larger droplet sizes of 50−100 μm.

These results are consistent with previous studies which have demonstrated better emulsifying ability of proteins when

compared to carbohydrates (*12*, *13*). Emulsifying activity of defatted macadamia flours has also been shown to be dependent on protein content (*14*). The importance of proteins is further reflected in the fact that Accu-gel, which is 99% starch, produced emulsions with significantly higher ($p < 0.05$) droplet sizes at pH 5.0 and pH 7.0 than the flours with 3−10% protein content. Previous work has also shown that flours with lower ratios of nonprotein to protein components have better emulsion forming ability (*15*). It is possible that at pH 3.0 and coupled with the high rate of shear (20,000 rpm) used for emulsion formation a slight acid-induced disruption of starch granule structure could have released modified (hydrolyzed) starch polymeric molecules, which enhanced the emulsifying ability of Accu-gel when compared to its emulsifying ability at pH 5.0 and 7.0. This is similar to a previous report that showed enhanced emulsion forming capacity of hydrolyzed starch when compared to unhydrolyzed starch (*16*).

The emulsifying capability of PPI was significantly higher ($p < 0.05$) at all concentrations than that of SPI when emulsions were formed at pH 5.0 and 7.0. The oil droplet size range was 14−16 μm for PPI and 38−42 μm for SPI. However, at a pH of 3.0 there was a higher emulsifying effect only at the lowest concentration of 10 mg/mL. In a previous work, it was shown that PPI had better emulsion forming ability than SPI at pH 5.0, but not at pH 7.0 (*17*). PPI has higher levels of sugars than SPI, which may contribute to increased solubility of the pea proteins and better emulsification capacity. The result is in agreement with a previous report that showed a positive relationship between protein solubility of pea or soybean proteins and emulsification capacity (*17*). Previous work has also shown that commercial PPI has more polypeptide chains (2 legumin and 7 vicillin) when compared to commercial SPI (2 legumin and 2 β-conglycinin) as revealed by gel electrophoresis (*1*). Thus the higher emulsifying capacity (lower oil droplet size) of the PPI may be due to the wider variety of polypeptide chains available for oil droplet formation. Our results differ from previous research reported by Tömösközi et al. (*18*), which indicated that SPI had better emulsion forming ability than PPI. However these contradictory results could be due to the processing history of the protein isolates. In our work commercial samples were used, rather than protein isolates prepared in the laboratory. There seem to have been very minimal changes in structural properties of the polypeptides present within the PPI in the pH range from 3.0 to 7.0, as evident from the lack of any significant change ($p < 0.05$) in average emulsion droplet size. Therefore, the results suggest that the pea isolate proteins were more resistant to changes in pH than the proteins of the soybean isolate. Our results are in contrast with previous work which showed increased oil droplet coalescence and droplet size of soybean-stabilized emulsions at pH 5.0 when compared to those at pH 3.0 and 7.0 (*12*). The differences in results could be due to the type of emulsions used; we used higher concentrations of proteins and lower homogenization pressure when compared to the work of Roudsari et al. (*12*), who used lower protein concentrations but very high homogenization pressure. In the present work, emulsion stability was measured after a short duration of 30 min when compared to 15 days for the previous work (*12*). Moreover the mean particle size of emulsions in this work is higher than values reported by Roudsari et al. (*12*).

Uptake 80 and Centu-tex have the same proximate composition but differ in the mean particle size of the flours, 175 and 425 μm, respectively (**Table 1**). Emulsions formed by Uptake 80 had droplets ranging from 29 to 40 μm compared to ones of 37−51 μm for Centu-tex emulsions. These results suggest that smaller particle size enhances emulsion formation, while large particle size has detrimental effects, since these products have identical chemical composition. Smaller particles could enhance the dispersion of the emulsifying components thus increasing interactions with the oil−water interface and improving formation of interfacial membranes. Larger flour particles would then be expected to reduce dispersion of the emulsifying components, including the polypeptides that facilitate reduction of interfacial tension, and so resulting in poorer emulsion formation. Oil droplet size distribution in the emulsions is shown in **Figure 2**. The main difference is the narrow range of the size of oil droplets (10−100 μm) formed by soybean proteins in comparison to the wider range of size (2−1000 μm) observed for the other emulsions. Therefore, the SPI-stabilized emulsions had more uniform size of oil droplets, which is an indication of the protein's ability to completely coat the oil droplets during homogenization and prevent their coalescence after homogenization (*19*). The results indicate that there is more complete interaction of SPI proteins with the emulsified oil droplets during homogenization, which aids in dispersing their larger sized aggregates into smaller sized particles to produce a narrow range of oil droplet size. Similar results were obtained for SPI-stabilized emulsions at different oil

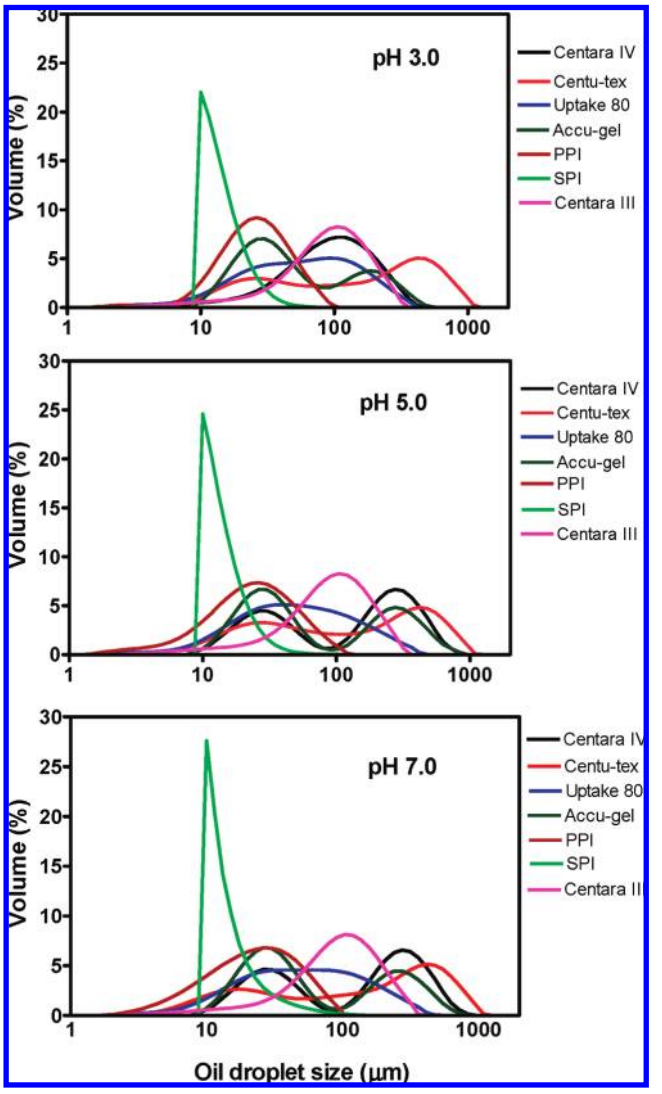

Figure 2. Oil droplet size distribution of emulsions stabilized by soybean protein isolate (SPI, 90% protein) and pea seed flours: Centara III and Centara IV (high fiber, >90%); Centu-Tex and Uptake 80 (starch 35%, fiber 50%); Accu-Gel, high starch (>98%); pea protein isolate (PPI, 82% protein).

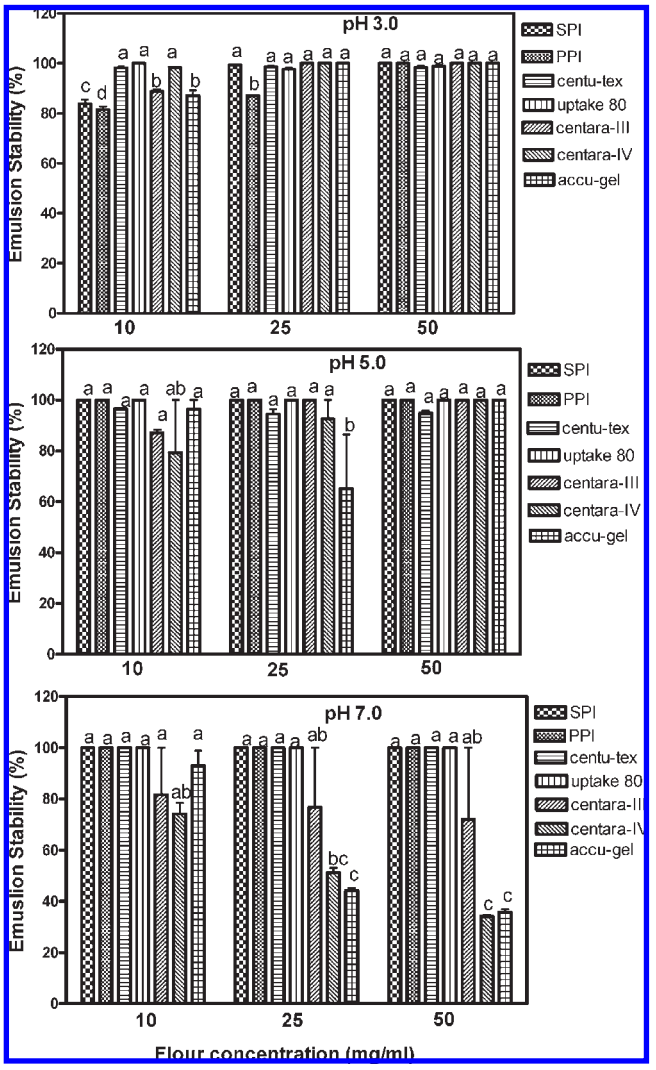

Figure 3. Effect of pH on the emulsifying stability (percent increase in oil droplet size) of soybean protein isolate (SPI, 90% protein) and pea seed flours: Centara III and Centara IV (high fiber, >90%); Centu-Tex and Uptake 80 (starch 35%, fiber 50%), Accu-Gel, high starch (>98%), pea protein isolate (PPI, 82% protein). For each box plot, bars with different letters are significantly different ($p < 0.05$).

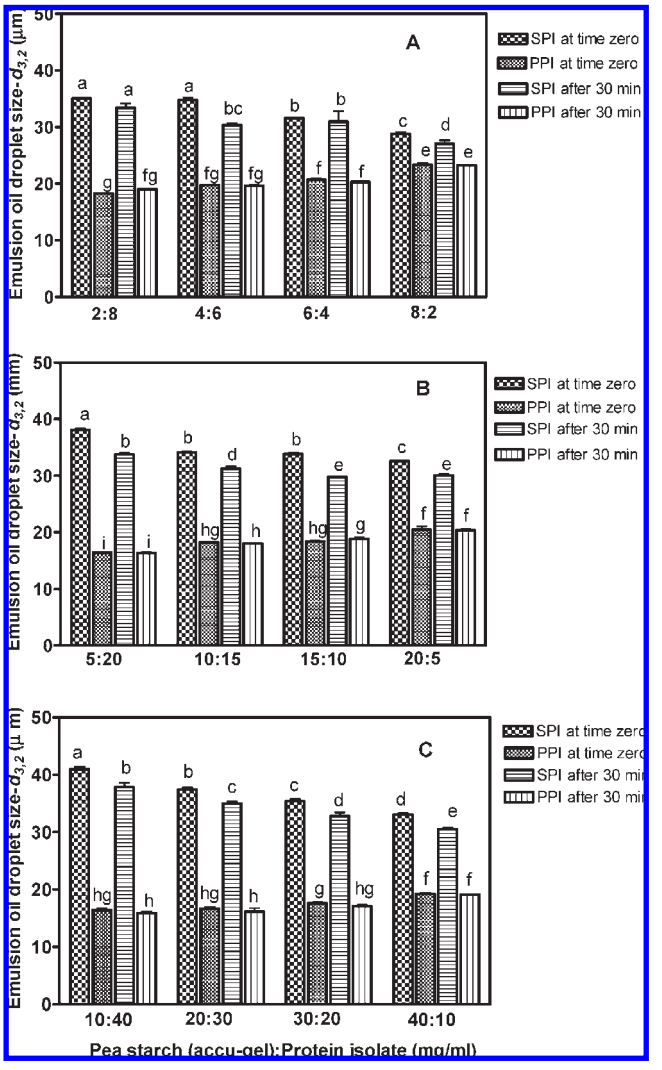

Figure 4. Emulsifying capacity (oil droplet size at time zero) and stability (oil droplet size after 30 min) of pea seed starch/protein combinations at pH 7.0. For each box plot, bars with different letters are significantly different ($p < 0.05$).

concentrations where formation of narrow range of oil droplet size was attributed to increased SPI−oil droplet interactions (*20*). Formation of larger size droplets has also been attributed to reduction in the degree of hydrogen bond-mediated interactions between the electric layer of ions on the oil droplets and surfactant (proteins or carbohydrates) molecules (*21*). It is possible that the pea proteins and carbohydrates found in the pea flours had weaker interactions with the oil droplet electric layer, which resulted in the larger sizes of the emulsion droplets when compared to the soybean proteins.

Emulsion stability is shown in **Figure 3**, and the results suggest significant differences ($p < 0.05$) at pH 3.0 mainly at low concentration of 10 mg/mL. In contrast there was an increase in the number of significantly different ($p < 0.05$) results at pH 7.0. Generally, all the emulsions were very stable (>80%) at all pH values except those made with starch (Accu-gel) and fiber (Centara III and Centara IV) products, which had decreased stability at pH 7.0. The high stability of these emulsions suggests that the pea seed flours may be suitable ingredients for the formulation of food emulsions that have good short-term stability properties.

Emulsion Quality of Starch−Protein Mixtures. Proteins are the main emulsifying agents in many foods, but the presence of carbohydrates within the food matrix can alter the emulsifying ability of the proteins and produce changes in food quality (*19*, *23*). Addition of starches to gluten-free products enhanced formation of the appropriate protein−starch networks needed to produce fermented bakery products (*24*). Starch products may be incorporated into foods to increase or decrease emulsion capacity in accordance with quality preferences of the manufacturer. **Figure 4** shows the effects of pea starch (Accu-gel) on the emulsifying properties of SPI and PPI at pH 7.0 and at varying ratios of starch to protein. A pH of 7.0 was used because this is near to the pH values of many manufactured foods. Emulsions formed using PPI had smaller oil droplets (better quality) than emulsions formed using SPI, a result similar to that obtained at pH 7.0 without the added starch (**Figure 1**). At pH 3.0, incorporation of starch significantly ($p < 0.05$) enhanced (lower oil droplet sizes) the emulsion formation by SPI, but had negative effects on emulsion formation by PPI. In fact at 10 mg/mL total sample concentration the ratio of 8 mg of starch to 2 mg of protein produced PPI and SPI emulsions with a difference of only about 5 μm in droplet size, as compared to 10−15 μm at lower concentrations of starch. The significant decrease ($p < 0.05$) in

droplet size of SPI emulsions was similar at the three sample concentrations, which suggests that the amount of sample used to make the emulsion did not affect the nature of starch−protein interactions. In research reported by Babiker et al. (*25*), the conjugation of a polysaccharide to soybean proteins also improved the emulsion forming ability of SPI.

It is important to emphasize that Accu-gel on its own produced very poor emulsions. Therefore, the ability of Accu-gel to improve emulsion forming ability of soybean proteins indicates a synergistic effect that may be attributed to starch−protein interactions. As discussed above, the poor emulsifying ability of SPI at pH 7.0 may be due to increased charge density, which prevents formation of strong interfacial protein membranes and smaller droplets. Therefore, it is reasonable to suggest that addition of pea starch to SPI may have led to a reduction in charge density, possibly as a result of neutralization of protein charges by oppositely charged starch residues. The emulsifying ability of soybean proteins has previously been found to be enhanced by the presence of soybean seed cotyledon polysaccharides (*12*) or through conjugation with dextran (*7*, *26*). The presence of the bulky starch molecules may also enhance formation of stable oil droplets by acting as physical barriers against oil droplet coalescence, which complements the emulsion forming ability of the proteins. The progressive nature of the improvement in emulsion forming ability of SPI with increases in starch concentration support our hypothesis that the protein−starch interactions favored decreased charge density at the oil−water interface and physical separation of the oil droplets. A decrease in charge density will enhance interactions at the oil−water interface and lead to the formation of strong interfacial membranes that produce emulsions of reduced droplet size. Similarly the interactions between SPI and pea starch could have improved the amphipathic properties of starch, giving enhanced emulsion forming ability when compared to starch alone. This type of synergy may be exploited in the manufacture of high quality SPI food emulsion products that incorporate optimal levels of pea starch. Similarly, during manufacture of cereal-based products such as protein enriched breakfast cereals, it has been shown that protein−starch interactions contribute to texture and rheological properties of dough (*27*). Thus, addition of pea starch to cereal-based ingredients could enhance incorporation of soybean proteins and produce high quality food products. In contrast, the results suggest that pea proteins did not interact with pea starch to produce any substantial change in emulsion forming ability. Therefore, we can deduce that the structural conformation of pea proteins at pH 7.0 was not changed by addition of starch, especially with respect to the ability to form interfacial membranes at the oil−water interface.

Figure 4 also shows that the emulsions containing combinations of pea starch and proteins were highly stable because there was no significant difference ($p > 0.05$) in emulsion oil droplet size between the $t = 0$ and $t = 30$ min measurements for each sample. The results are generally consistent with **Figure 3** where we have shown high levels of stability for emulsions made with the pea seed flours. Therefore, incorporation of starch into the protein flours did not have any negative effect on the ability of the proteins to stabilize oil-in-water emulsions.

Effect of Sample Concentration and pH on Foam Formation and Stability. Foam formation is an important requirement in the manufacture of foods such as ice cream, cakes and meringues. Therefore, the ability of the pea seed flours to form foams could be essential to their application in the manufacture of nondairy foods. For PPI and SPI, concentration significantly ($p < 0.05$) influenced foaming ability (foam volume), but for Centu-tex, Uptake 80, Centara III and IV, and Accu-gel, which had lower

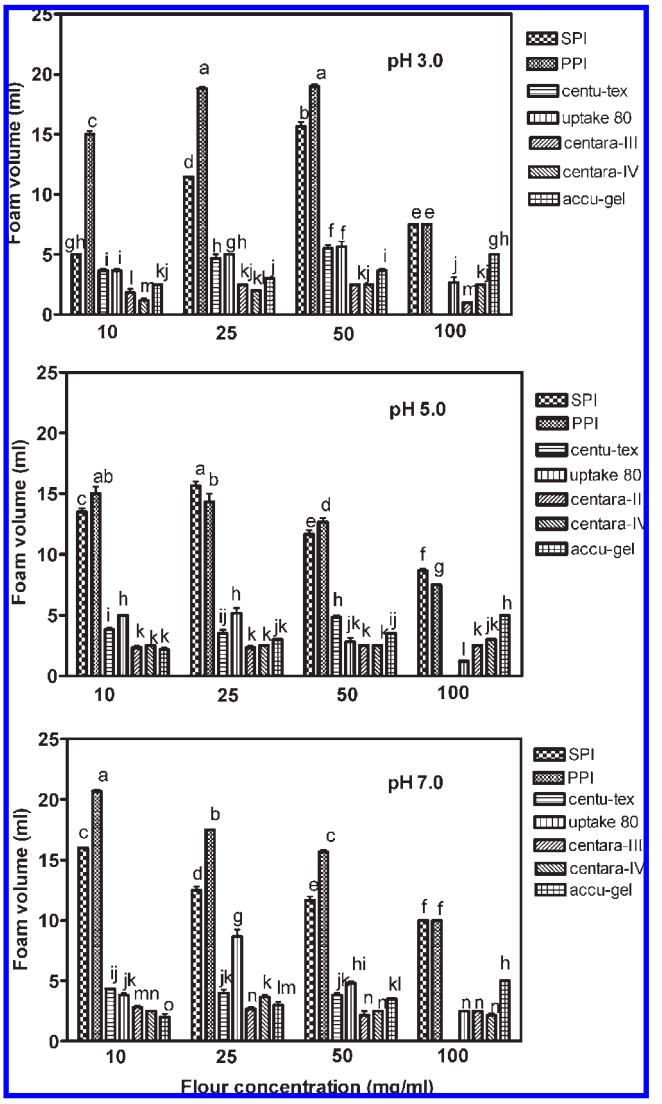

Figure 5. Effect of pH on the foaming capacity (foam volume) of soybean protein isolate (SPI, 90% protein) and pea seed flours: Centara III and Centara IV (high fiber, >90%); Centu-Tex and Uptake 80 (starch 35%, fiber 50%), Accu-Gel, high starch (>98%), pea protein isolate (PPI, 82% protein). For each box plot, bars with different letters are significantly different ($p < 0.05$).

foaming capacity, the effect of concentration was much less (**Figure 5**). Overall, SPI and PPI produced higher volume foams than the flours with lower protein concentrations. The results suggest that formation of interfacial protein membranes at the air−water interface enhanced encapsulation of air bubbles. Similar to the emulsion results, foam formation was largely dependent on the protein content of the samples. The foaming ability of PPI and SPI at pH 3.0, and concentrations of up to 50 mg/mL, increased as sample concentrations increased, while at a pH of 7.0 the foam volume decreased as concentrations increased. At the highest concentration (100 mg/mL) foaming ability was significantly reduced for all pH values. The results suggest that, at the high concentrations of surfactants used in this, there could have been limited solubility (dispersibility) in water that enhances foam breakage rather than foam formation. Effects of pH and concentration on the foam foaming ability of PPI and SPI differed considerably. At pH 3.0 and 7.0 and up to 50 mg/mL sample concentration, PPI had significantly higher ($p < 0.05$) foaming ability (15−22 mL) when compared to SPI (5−16 mL). The results suggest that PPI is a better foaming agent with a more

flexible polypeptide conformation at pH 3.0 and 7.0 when compared to SPI. The presence of higher levels of sugars (~12%) may have also enhanced foaming ability of the PPI when compared to SPI that had <1% sugar content (**Table 1**). Previous reports have also shown superior foaming properties of pea protein isolate when compared to SPI (*4*, *5*). However, our results are in contrast to those obtained by Tömösközi et al. (*18*), which showed poorer foaming ability of PPI when compared to SPI. At the highest sample concentration of 100 mg/mL, foam formation was decreased for PPI and SPI, suggesting excessive protein−protein interactions that would have limited ability to form flexible interfacial membranes that are required to encapsulate the air bubbles.

At pH 5.0, significant differences ($p < 0.05$) between the foaming abilities of PPI and SPI were observed and were concentration dependent (**Figure 5**). The foaming ability of 10 and 25 mg/mL concentrations of SPI was significantly higher ($p < 0.05$) at pH 5.0 when compared to that at pH 3.0. Since pH 5.0 is near the isoelectric point (p*I*) of soybean proteins, it is possible that the reduction in net charge density enhanced protein−protein interactions such that strong interfacial membranes are formed, which facilitated better foaming ability. At pH 7.0, foaming ability increased for PPI and SPI indicating better (compared to pH 3.0 and 5.0) structural conformation suitable for interfacial membrane formation. The results suggest that as the pH increased there were increases in the net charge density of PPI and SPI, which enhanced protein unfolding and flexibility that contributed to better foam formation. However, as the protein concentration increased, foaming ability was decreased at pH 5.0 probably as a result of increased protein−protein interactions or reduced solubility that decreased flexibility and ability to form efficient interfacial membranes. At pH 7.0, the increase in protein concentrations also led to significant decreases ($p < 0.05$) in foam volume, which could be attributed to excessive charge density or reduced solubility that prevented formation of interfacial membranes at the level required for efficient encapsulation of air bubbles. For SPI, there was an increase in foaming ability as the pH increased from acidic values (pH 3.0 and 5.0) to neutral value (pH 7.0), a result that is similar to those previously reported by Aluko et al. (*15*).

Particle size also affected the foaming ability of Centu-tex and Uptake 80, two samples with the same composition but different flour particle sizes of 425 and 175 μm, respectively. This is most noticeable at the highest sample concentration of 100 mg/mL where Centu-tex (large particle size) was unable to form any foam at the three pH values used in this work (**Figure 5**). In contrast, Uptake 80 (smaller particle size) still produced some foams with 100 mg/mL sample concentration at the three pH values, indicating availability of foaming agents. At a concentration of 25 mg/mL, the foaming ability of Uptake 80 was significantly increased ($p < 0.05$) at pH 7.0 when compared to pH 3.0 and 5.0. Therefore, the foaming agents (especially proteins) were more available within the smaller particle size of Uptake 80 and responded to the increase in pH by becoming more flexible with increased capacity to encapsulate air bubbles. The large particle size of Centu-tex flour may have imposed limitations to the availability of foaming agents at high concentrations which prevented formation of interfacial membranes. The results confirm that small particles of flours contribute to better foaming properties, especially at high sample concentrations where clumping can occur to limit interaction with the air−water interface.

Foam stability was highly dependent on pH and sample concentration as shown in **Figure 6**. At 10 mg/mL concentration only the high protein flours (SPI and PPI) produced stable foams at pH 5. Similarly only the foams produced by SPI and PPI were

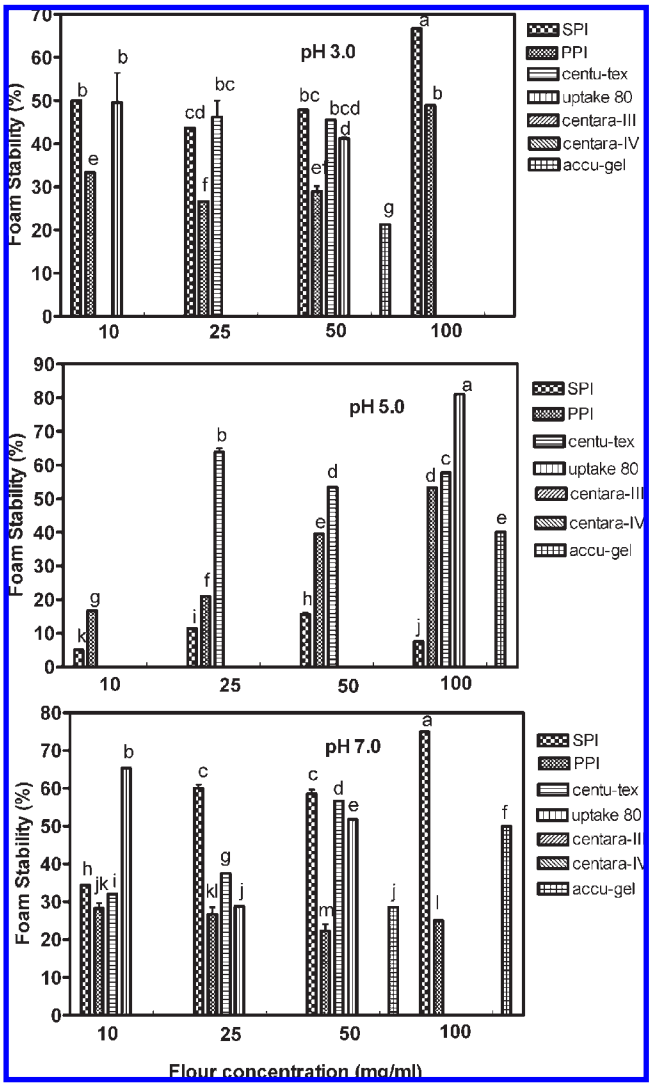

Figure 6. Effect of pH on the foam stability (percent decrease in foam volume) of soybean protein isolate (SPI, 90% protein) and pea seed flours: Centara III and Centara IV (high fiber, >90%); Centu-Tex and Uptake 80 (starch 35%, fiber 50%), Accu-Gel, high starch (>98%), pea protein isolate (PPI, 82% protein). For each box plot, bars with different letters are significantly different ($p < 0.05$).

stable at all the pH values and sample concentrations used in this work. The results suggest that proteins are more important than nonprotein components with respect to foam stabilization. The number of stable foams was higher at pH 7.0 when compared to pH 3.0 and 5.0, which suggests increased formation of strong interfacial membranes as acidity level of the environment was reduced. At the highest sample concentration (100 mg/mL) used in this work the number of stable foams (5) was higher at pH 5.0 when compared to pH 3.0 (2 foams) and pH 7.0 (3 foams). Therefore, high sample concentration could be used to remedy poor foam stability properties of these flours at pH 5.0.

Foaming Quality of Starch−Protein Mixtures. Protein−polysaccharide interactions are also known to affect foaming properties since nonspecific interactions can lead to attractive and repulsive forces that induce complex formation or immiscibility of biopolymers (*18*). The effects of pea starch on foaming abilities of PPI and SPI are shown in **Figure 7**. When compared to the results shown in **Figure 5**, it can be seen that the initial incorporation of 20% pea starch actually enhanced foaming ability of SPI but not PPI. For example, foaming capacity of SPI at pH 7.0 and

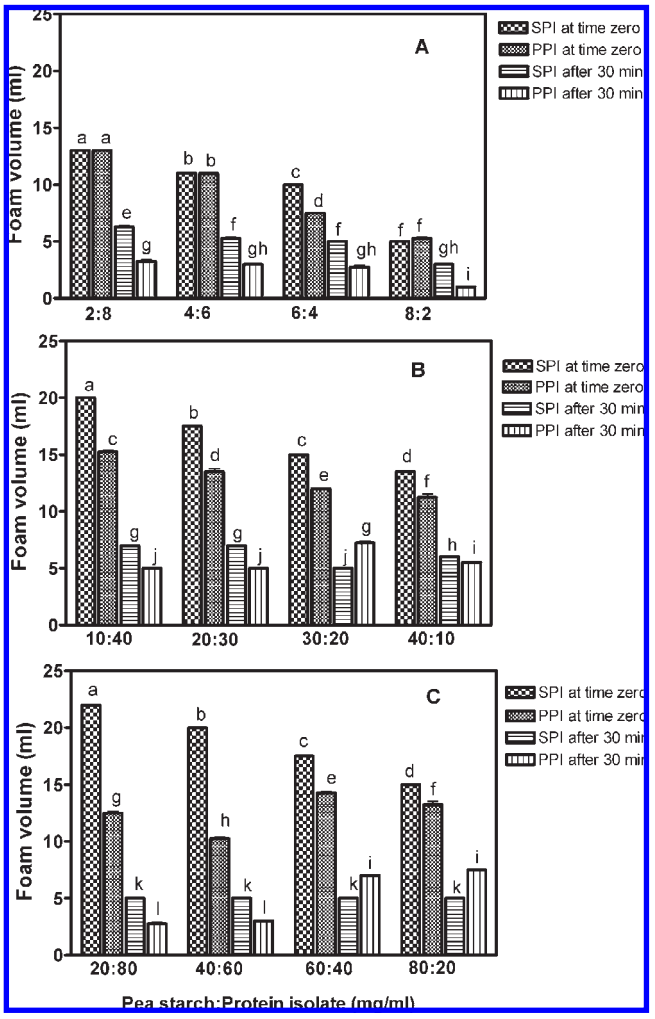

Figure 7. Foaming capacity (foam volume at time zero) and stability (foam volume after 30 min) of pea seed starch/protein combinations at pH 7.0. For each box plot, bars with different letters are significantly different ($p < 0.05$).

50 and 100 mg/mL was 12 and 10 mL (**Figure 5C**), respectively, when compared to 20 and 22 mL for 10:40 and 20:80 starch: protein ratios (**Figures 7B** and **7C**), respectively. The result for SPI is similar to a previous work which showed that addition of potato starch (25% level) led to 54% increase in foaming ability of lupin seed protein concentrate (*28*). Unlike the emulsion results, increased incorporation of pea starch led to significant reductions ($p < 0.05$) in the ability of PPI and SPI to form foams with up to 50% decrease in foam volume. The results suggest that interactions of pea starch with soybean and pea proteins led to reduced formation of interfacial membranes that are required to encapsulate the air bubbles. The effects of pea starch on foam formation are opposite the trend obtained for emulsion formation, which is an indication of different mechanisms involved during interfacial membrane formation at the air−water and oil−water interfaces. Since the oil−water interface is more hydrophobic than the air−water interface, it is possible that the interaction of starch with proteins produced more hydrophobic complexes which favor greater interactions with the oil−water interface when compared to the air−water interface. In general, foaming ability was significantly improved ($p < 0.05$) with increasing concentrations of sample size from 10 mg/mL (**Figure 7A**) to 100 mg/mL (**Figure 7C**) at all levels of starch substitution. Therefore, at low sample concentrations there were not enough protein/starch complexes to form sufficient interfacial membranes that will encapsulate the air bubbles. But as the sample concentrations increased, more interfacial membranes could be formed, which enhanced foam formation. This trend is especially noticeable for SPI which had a maximum of 13 mL of foam at 10 mg/mL (**Figure 7A**) when compared to 23 mL of foam at 100 mg/mL (**Figure 7C**) sample concentration. Just as observed for emulsion formation, the presence of low levels of pea starch led to improved foam formation by SPI when compared to the amount of foam formed by SPI alone. However, unlike the trend observed with emulsion formation, increased ratios of starch to protein had significant ($p < 0.05$) negative effects on foam formation. Foaming capacity of the pea starch/protein mixtures was significantly reduced ($p < 0.05$) during short-term (30 min) storage at room temperature as shown by the lower foam volumes obtained after 30 min (**Figure 7**). Thus, unlike the emulsions, pea starch did not improve foam stability of soybean and pea proteins.

The present results showed that emulsion and foam formations were dependent on protein levels in the pea flours with the protein-deficient flours giving poor results. It is evident that interfacial membrane formation at the oil−water and air−water interfaces is highly dependent on protein−protein interactions to provide good emulsion and foam forming abilities. A smaller particle size enhanced the emulsion and foam forming abilities of flours, which may be attributed to greater availability of interfacial pressure-lowering components of the flour. In contrast, large particles limit availability of the interfacial pressure-lowering components, and lead to poor emulsion and foam forming abilities. The improvement in the emulsion forming capability of soybean protein with the addition of pea starch could be the result of favorable protein−starch interactions. This could be exploited to enhance the quality of soybean-based food emulsions. Overall, the superior emulsion and foam forming abilities of PPI may be exploited in the food industry as suitable replacement of traditional soybean-stabilized food emulsions, especially in the manufacture of hypoallergenic foods for people allergic to soybean proteins.

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